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**Title:** Anomalous  $Wtb$  coupling and forward-backward asymmetry of top quark production at the Tevatron

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**Citation style:** Kołodziej Karol. (2016). Anomalous  $Wtb$  coupling and forward-backward asymmetry of top quark production at the Tevatron. "Physics Letters B" (Vol. 710, iss. 4-5 (2016), s. 671-675), doi 10.1016/j.physletb.2012.03.055



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# Anomalous $Wtb$ coupling and forward–backward asymmetry of top quark production at the Tevatron

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## ARTICLE INFO

### Article history:

Received 11 October 2011

Received in revised form 13 February 2012

Accepted 22 March 2012

Available online 24 March 2012

Editor: T. Yanagida

## ABSTRACT

An influence of the anomalous  $Wtb$  coupling on forward–backward asymmetry in top quark pair production at the Tevatron is investigated taking into account decays of the top quarks to 6 fermion final states containing one charged lepton. To this end the most general effective Lagrangian of the  $Wtb$  interaction containing terms of dimension up to five is implemented into `carlomat`, a general purpose Monte Carlo program, which allows to compute automatically all necessary cross sections in the presence of anomalous vector and tensor form factors. A sample of results which illustrate little effect of the left- and right-handed tensor form factors on the  $t\bar{t}$  invariant mass dependent forward–backward asymmetry and the charge-signed rapidity distribution of the lepton originating from the  $W$  boson from top quark decay is shown.

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## 1. Introduction

The top quark is the heaviest particle ever observed, with mass close to the energy scale of the electroweak symmetry breaking. Therefore the top quark physics is an ideal place to look for non-standard effects which may reveal themselves through departures of the top quark properties and interactions from those predicted by the standard model (SM). The observation of a forward–backward asymmetry (FBA) in the top quark pair production in high energy proton–antiproton collisions at Tevatron [1,2] that exceeds the SM expectation is an indication that this conjecture may be true. The CDF and D0 Collaborations measured the total asymmetry  $A_{t\bar{t}}$  at a parton-level:

$$A_{t\bar{t}}(\text{CDF}) = 0.158 \pm 0.075, \quad A_{t\bar{t}}(\text{D0}) = 0.196 \pm 0.06,$$

which is higher, but not inconsistent with the SM result. The asymmetry is zero in the lowest order of SM. A small asymmetry of  $A_{t\bar{t}} = 0.06 \pm 0.01$  arises at one loop QCD in the result of interferences of double-gluon corrections that differ under charge conjugation [3]. The CDF Collaboration finds that the asymmetry is a rising function of the  $t\bar{t}$  invariant mass  $m_{t\bar{t}}$ , with

$$A_{t\bar{t}}(m_{t\bar{t}} \geq 450 \text{ GeV}/c^2) = 0.475 \pm 0.114,$$

which is more than three standard deviations above the SM prediction in this  $m_{t\bar{t}}$  region [1]. The D0 Collaboration measured also a corrected asymmetry based on the lepton from a top quark decay

to be  $0.152 \pm 0.040$  which should be compared with the next-to-leading-order Monte Carlo generator result of  $0.021 \pm 0.001$  [4]. Dedicated analyses of higher order contributions to the FBA of top quarks in the high invariant mass range of  $m_{t\bar{t}} > 450 \text{ GeV}/c^2$  show that the inclusion of the higher order QCD [5] and electroweak [6,7] corrections increases the one loop QCD prediction to some extent, but a  $3\sigma$  deviation between the measurement and the SM prediction in this range still remains. Several new physics ideas, which alter the SM top quark production mechanism, have been invoked in order to explain the discrepancy [8].

At the Tevatron, the top quarks are produced dominantly in pairs through the quark–antiquark annihilation process

$$q\bar{q} \rightarrow t\bar{t}. \quad (1)$$

Creation of a top quark pair through the gluon–gluon fusion process,  $gg \rightarrow t\bar{t}$ , that dominates the top quark production at the LHC, has much smaller cross section at the Tevatron. Moreover, it does not contribute to the FBA, as its initial state is symmetric under charge conjugation. Single top production processes, as e.g.  $q\bar{b} \rightarrow q't$ ,  $q\bar{q}' \rightarrow t\bar{b}$  or  $qg \rightarrow q'tb$ , have much smaller cross sections at the Tevatron, therefore their possible contribution to the FBA is neglected in the present work.

Each of the top quarks of reaction (1) decays into a  $b$  quark and a  $W$  boson before hadronization takes place, and the  $W$  bosons decay into a fermion–antifermion pair each. The top quark pair production at the Tevatron is identified by selecting events where one  $W$  decays to  $q\bar{q}'$  and the other to  $l\bar{\nu}_l$ . The experimental signature is an isolated electron or muon with large transverse momentum, a missing transverse momentum from the undetected

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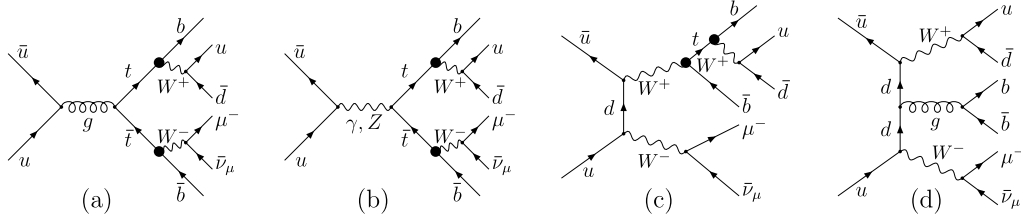


Fig. 1. Examples of the lowest order Feynman diagrams of reaction (3). Black blobs indicate the  $Wtb$  coupling.

neutrino and four or more jets. At the parton level, one should consider reactions of the form

$$u\bar{u}(d\bar{d}) \rightarrow bq\bar{q}'\bar{b}l\bar{\nu}_l, \quad (2)$$

where the quark  $q$  in the final state may be  $b$ , but need not be identical with the initial state  $u$  or  $d$  quark. Any specific channel of (2) receives contributions typically from a few hundred Feynman diagrams, already at the lowest order of SM. For example, in the unitary gauge, assuming vanishing light fermion masses,  $m_u = m_d = m_s = m_e = m_\mu = 0$ , and neglecting the Cabibbo–Kobayashi–Maskawa (CKM) mixing between quarks, there are 718 lowest order Feynman diagrams for each of the reactions

$$u\bar{u} \rightarrow b\bar{d}\bar{b}\mu^-\bar{\nu}_\mu, \quad (3)$$

$$d\bar{d} \rightarrow u\bar{b}\bar{b}\mu^-\bar{\nu}_\mu. \quad (4)$$

Examples of the Feynman diagrams of reaction (3) are shown in Fig. 1. They include only six ‘signal’ diagrams of  $t\bar{t}$  production, three of which are depicted in Figs. 1(a) and 1(b) and the other three are obtained by permutation of identical  $u$  quarks. All the remaining diagrams constitute the off resonance background for the top quark pair production process. Some of them, as the one shown in Fig. 1(c), may contain a single top quark propagator, but most of the diagrams do not contain the internal top quark line at all, as the one shown in Fig. 1(d). Let us note that the  $Wtb$  coupling that is indicated by a black blob enters twice both in the  $t\bar{t}$  production signal diagrams and the diagram with one top quark propagator. Obviously, it is not present in the off resonance background diagrams without internal top quark lines.

The presence of an anomalous  $Wtb$  coupling influences the top quark pair production in two basic ways. First, it changes the total decay width of the top quark, which substantially alters the total cross sections of any of reactions (2). Secondly, it changes the differential distributions of the final state particles, in particular of the final state lepton, which may have some influence on the  $t\bar{t}$  production event reconstruction.

Therefore, in the present Letter, the anomalous  $Wtb$  coupling of the most general form, with operators up to dimension five, is included in the theoretical analysis in order to see to which extent its possible modifications may change lowest order SM predictions for the  $t\bar{t}$  invariant mass dependent FBA in the top quark pair production at the Tevatron. The question of whether the anomalous  $Wtb$  coupling may affect the asymmetry based on the charge and rapidity of the muon originating from the  $W$  boson from top quark decay will also be addressed.

## 2. An anomalous $Wtb$ coupling

The effective Lagrangian of the  $Wtb$  interaction containing operators of dimension four and five considered in the present Letter has the following form [9]:

$$L_{Wtb} = \frac{g}{\sqrt{2}} V_{tb} \left[ W_\mu^- \bar{b} \gamma^\mu (f_1^L P_L + f_1^R P_R) t \right.$$

$$\begin{aligned} & - \frac{1}{m_W} \partial_\nu W_\mu^- \bar{b} \sigma^{\mu\nu} (f_2^L P_L + f_2^R P_R) t \Big] \\ & + \frac{g}{\sqrt{2}} V_{tb}^* \left[ W_\mu^+ \bar{t} \gamma^\mu (\bar{f}_1^L P_L + \bar{f}_1^R P_R) b \right. \\ & \left. - \frac{1}{m_W} \partial_\nu W_\mu^+ \bar{t} \sigma^{\mu\nu} (\bar{f}_2^L P_L + \bar{f}_2^R P_R) b \right], \end{aligned} \quad (5)$$

where  $g$  is the weak coupling constant,  $m_W$  is the mass of the  $W$  boson,  $P_L = \frac{1}{2}(1 - \gamma_5)$  and  $P_R = \frac{1}{2}(1 + \gamma_5)$  are the left- and right-handed chirality projectors,  $\sigma^{\mu\nu} = \frac{i}{2}[\gamma^\mu, \gamma^\nu]$ ,  $V_{tb}$  is the element of the CKM matrix with the superscript  $*$  denoting complex conjugate,  $f_i^L$ ,  $f_i^R$ ,  $\bar{f}_i^L$  and  $\bar{f}_i^R$ ,  $i = 1, 2$ , are form factors which can be complex in general. There are also other dimension five terms possible in Lagrangian (5) for off shell  $W$  bosons, but they have been neglected as they vanish if the  $W$ 's decay into massless fermions, which is a very good approximation for fermions lighter than the  $b$  quark. Therefore, in this approximation, Eq. (5) represents the most general effective Lagrangian of the  $Wtb$  interaction containing terms of dimension up to five.

The lowest order SM Lagrangian of the  $Wtb$  interaction is reproduced by setting

$$f_1^L = \bar{f}_1^L = 1, \quad f_1^R = f_2^R = f_2^L = \bar{f}_1^R = \bar{f}_2^R = \bar{f}_2^L = 0 \quad (6)$$

in (5). If  $CP$  is conserved then the following relationships between the form factors hold

$$\bar{f}_1^{R*} = f_1^R, \quad \bar{f}_1^{L*} = f_1^L, \quad \bar{f}_2^{R*} = f_2^L, \quad \bar{f}_2^{L*} = f_2^R \quad (7)$$

and 4 independent form factors are left in Lagrangian (5). The Feynman rules resulting from Lagrangian (5) are as follows [11]:

$$\begin{aligned} t \rightarrow b W_\mu^+ & \rightarrow \Gamma_{t \rightarrow b W^+}^\mu = \frac{g}{\sqrt{2}} V_{tb} \left[ \gamma^\mu (f_1^L P_L + f_1^R P_R) \right. \\ & \left. - i \frac{q_\nu}{m_W} \sigma^{\mu\nu} (f_2^L P_L + f_2^R P_R) \right], \end{aligned} \quad (8)$$

and

$$\begin{aligned} \bar{t} \rightarrow \bar{b} W_\mu^- & \rightarrow \Gamma_{\bar{t} \rightarrow \bar{b} W^-}^\mu = \frac{g}{\sqrt{2}} V_{tb}^* \left[ \gamma^\mu (\bar{f}_1^L P_L + \bar{f}_1^R P_R) \right. \\ & \left. - i \frac{q_\nu}{m_W} \sigma^{\mu\nu} (\bar{f}_2^L P_L + \bar{f}_2^R P_R) \right], \end{aligned} \quad (9)$$

where  $q$  is a four momentum of the  $W$  boson outgoing from the  $Wtb$  vertex.

Direct Tevatron limits, that have been obtained by investigating two form factors at a time and assuming the other two at their SM values, are the following [12]<sup>1</sup>:

$$|f_1^R|^2 < 1.01, \quad |f_2^R|^2 < 0.23, \quad |f_2^L|^2 < 0.28. \quad (10)$$

The direct LHC limits that have been discussed in [14] are still weaker. If  $CP$  is conserved then the right-handed vector coupling and tensor couplings can be indirectly constrained from the CLEO data on  $b \rightarrow s\gamma$  [15] and from other rare  $B$  decays [16]. However, there is still some room left within which the anomalous form factors can be varied, in particular the tensor ones.

The anomalous  $Wtb$  couplings (8) and (9) are implemented into `carlomat`, a general purpose program for Monte Carlo (MC) computation of lowest order cross sections [10]. A new version of the program obtained in this way allows to make predictions for the top quark production and decay through different possible partonic subprocesses while taking into account complete sets of the lowest order Feynman diagrams and full information on spin correlations between the top quark and its decay products. The new version of `carlomat` can also be applied for studying anomalous effects in the top quark production and decay at the LHC, or in  $e^+e^-$  collisions at a linear collider [17,18].

### 3. Results

In this section, a sample of results that illustrate the influence of the tensor form factors of anomalous  $Wtb$  couplings (8) and (9) on the  $t\bar{t}$  invariant mass dependent asymmetry in the top quark production and on the charge-signed muon rapidity distribution at the high energy  $p\bar{p}$  collisions at the Tevatron is shown. The results have been obtained with the current version of `carlomat`.

The physical input parameters that are used in the computation are the following: the gauge boson masses and widths

$$m_W = 80.419 \text{ GeV}, \quad \Gamma_W = 2.12 \text{ GeV}, \\ m_Z = 91.1882 \text{ GeV}, \quad \Gamma_Z = 2.4952 \text{ GeV}, \quad (11)$$

the heavy quark masses and the Higgs boson mass

$$m_t = 172.5 \text{ GeV}, \quad m_b = 4.4 \text{ GeV}, \quad m_H = 115 \text{ GeV} \quad (12)$$

and the coupling constants

$$\alpha_W = 1/132.5049458, \quad \alpha_s(m_Z) = 0.118. \quad (13)$$

The QCD couplings are parametrized by  $g_s = \sqrt{4\pi\alpha_s}$ . The electroweak coupling constants are parametrized in terms of  $g = \sqrt{4\pi\alpha_W}$  and the complex electroweak mixing parameter  $\sin^2\theta_W = 1 - M_W^2/M_Z^2$ , with the complex masses of the  $W$  and  $Z$  bosons  $M_V^2 = m_V^2 - im_V\Gamma_V$ ,  $V = W, Z$ . The complex gauge boson masses together with the complex masses of the Higgs boson and top quark  $M_H^2 = m_H^2 - im_H\Gamma_H$  and  $M_t = \sqrt{m_t^2 - im_t\Gamma_t}$ , where  $\text{Re } M_t > 0$ , replace masses in the corresponding propagators, both in the  $s$ - and  $t$ -channel Feynman diagrams. This choice of parameterizations is referred to as the ‘complex mass scheme’ in `carlomat`. The Higgs boson width is fixed at the lowest order SM value  $\Gamma_H = 4.9657 \text{ MeV}$  and the width of the top quark is calculated to the lowest order with effective Lagrangian (5) for any specific choice of the form factors.

The  $t\bar{t}$  invariant mass dependent forward–backward asymmetry  $A_{t\bar{t}}$  is defined by

$$A_{t\bar{t}}(m_{t\bar{t},i}) = \frac{\sigma(\Delta y > 0, m_{t\bar{t},i}) - \sigma(\Delta y < 0, m_{t\bar{t},i})}{\sigma(\Delta y > 0, m_{t\bar{t},i}) + \sigma(\Delta y < 0, m_{t\bar{t},i})}, \quad (14)$$

with  $\Delta y = y_t - y_{\bar{t}}$  being a difference of rapidities of the  $t$  and  $\bar{t}$  quarks with their invariant mass  $m_{t\bar{t}}$  within  $i$ -th bin. Since  $\Delta y$  is independent of boosts along the beam axis, asymmetry (14) can be regarded as measured in the  $t\bar{t}$  centre of mass system.

The cross section of top quark pair production in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96 \text{ TeV}$  of Eq. (14) is calculated by folding CTEQ6L parton distribution functions [19] with the cross section of hard scattering subprocess of the top quark pair production of the form (2), including all the subprocesses with  $u\bar{u}$  and  $d\bar{d}$  in the initial state and a single charged lepton in the final state, as e.g. processes (3) and (4). The factorization scale is assumed to be equal to a square of the reduced centre of mass system energy,  $\hat{s} = x_1 x_2 s$ , with  $x_1$  ( $x_2$ ) being a fraction of energy carried by the initial state quark (antiquark). The  $t\bar{t}$  production events are identified with the following acceptance cuts on the transverse momenta  $p_T$ , pseudorapidities  $\eta$ , missing transverse energy  $\cancel{E}^T$  and separation  $\Delta R_{ik} = \sqrt{(\eta_i - \eta_k)^2 + (\varphi_i - \varphi_k)^2}$  in the pseudorapidity–azimuthal angle ( $\varphi$ ) plane between the objects  $i$  and  $k$ :

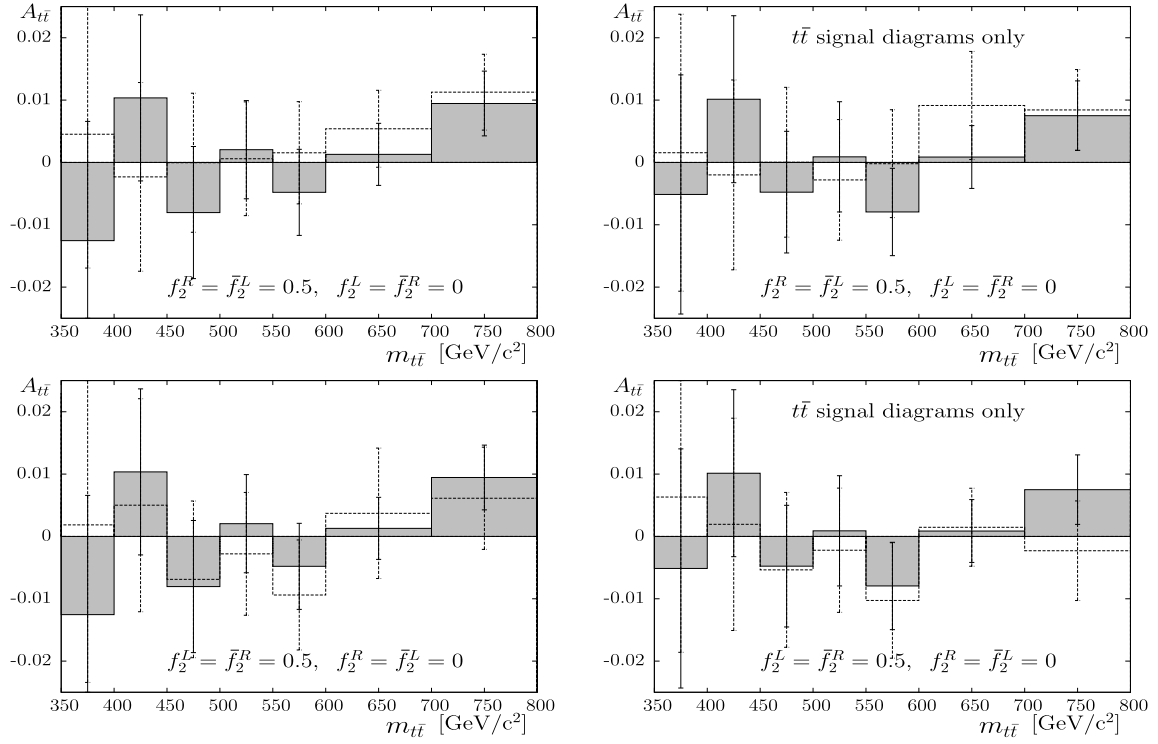
$$p_{Tl} > 50 \text{ GeV}/c, \quad p_{Tj} > 50 \text{ GeV}/c, \\ |\eta_l| < 2.0, \quad |\eta_j| < 2.5, \\ \cancel{E}^T > 20 \text{ GeV}, \quad \Delta R_{ll,jj} > 0.4. \quad (15)$$

The subscripts  $l$  and  $j$  in (15) stand for *lepton* and *jet*, a direction of the latter being identified with the direction of the corresponding quark. Cuts (15) are rather restrictive. It has been checked by a direct computation that only events with the invariant masses of  $bq\bar{q}'$  and  $b\bar{l}\bar{v}_l$  subsystems each close to  $m_t$  survive. This means that the off resonance background contributions are heavily suppressed and asymmetry (14) is in practice dominated by the events of  $t\bar{t}$  production and decay.

For the sake of simplicity, it is assumed that  $V_{tb}$  and form factors  $f_i^L$ ,  $f_i^R$ ,  $\tilde{f}_i^L$  and  $\tilde{f}_i^R$ ,  $i = 1, 2$ , of Lagrangian (5) are real. As the global fit combined with the SM constraints gives  $|V_{tb}| = 0.999152^{+0.000030}_{-0.000045}$  [20], a value of  $V_{tb}$  is fixed at  $V_{tb} = 1$ . Moreover, the vector form factors are assumed at their SM values of (6),  $f_1^L = \tilde{f}_1^L = 1$ ,  $f_1^R = \tilde{f}_1^R = 0$  and only the tensor form factors are being varied.

In Fig. 2, asymmetry (14) is plotted as a function of  $m_{t\bar{t}}$ , in bins of  $50 \text{ GeV}/c^2$  below  $600 \text{ GeV}/c^2$  and  $100 \text{ GeV}/c^2$  above that. The plots in panels on the left hand side have been obtained with the complete set of the lowest order Feynman diagrams of each contributing subprocess and those in panels on the right hand side have been obtained with the  $t\bar{t}$  signal Feynman diagrams only. The result that corresponds to the form factors satisfying lowest order SM relations (6) is depicted with grey boxes in each panel, with solid error bars showing one standard deviation of the MC integration in separate bins. Boxes bounded by dashed lines show the asymmetry in the presence of two  $CP$ -even combinations of tensor form factors:  $f_2^R = \tilde{f}_2^L = 0.5$ ,  $f_2^L = \tilde{f}_2^R = 0$  in the upper raw panels and  $f_2^L = \tilde{f}_2^R = 0.5$ ,  $f_2^R = \tilde{f}_2^L = 0$  in the lower raw panels. The error bars drawn with dashed lines show the corresponding one standard deviation of the MC integration in separate bins. There are some fluctuations visible in separate bins, but they do not exceed  $2\sigma$ . Also the total lowest order asymmetry computed with `carlomat` is consistent with zero within one standard deviation of the MC integration, as it is shown in Table 1. The asymmetry plots for other combinations of the tensor form factors, including the  $CP$ -odd ones, look very similar, so they are not shown here. Needless to say, the effect of the anomalous form factors becomes smaller if they are chosen within the recent D0 limits [13].

<sup>1</sup> After this work had been submitted for publication new one-dimensional direct constraints at 95% C.L. on the form factors were announced by the D0 Collaboration [13]:  $|V_{tb}f_1^R|^2 < 0.93$ ,  $|V_{tb}f_2^R|^2 < 0.13$ ,  $|V_{tb}f_2^L|^2 < 0.06$ .

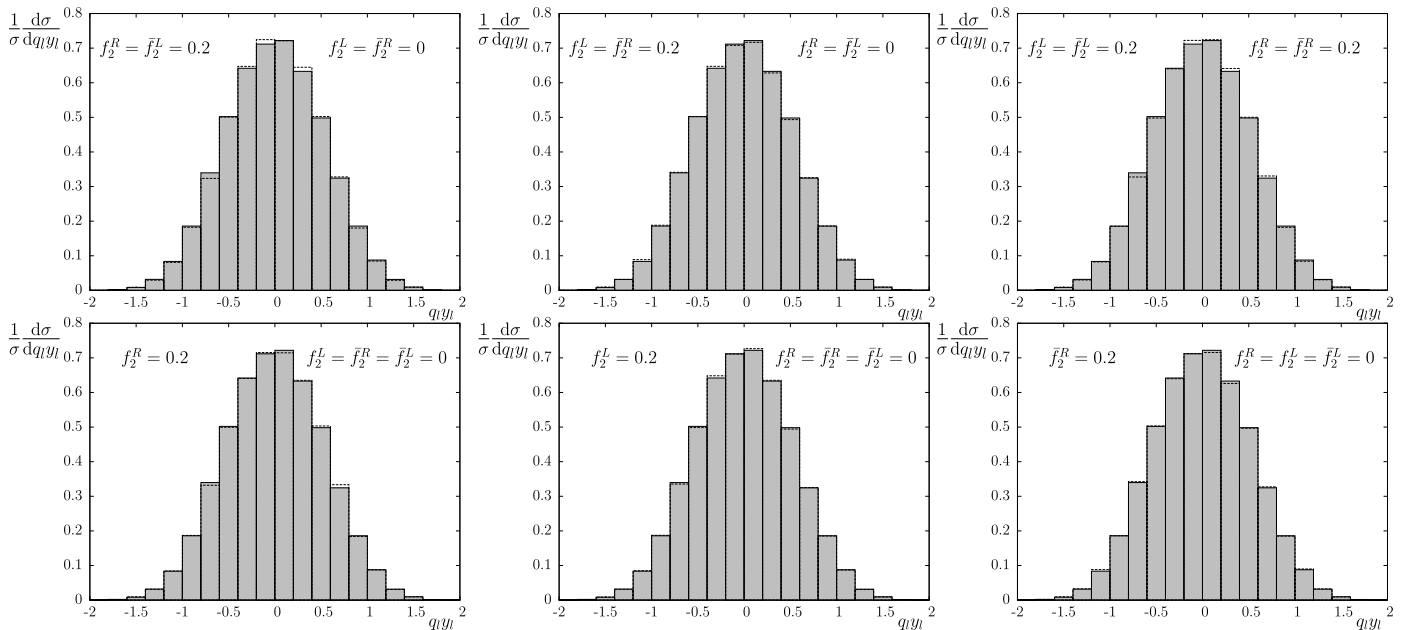


**Fig. 2.** Asymmetry (14) calculated with the complete set of the lowest order Feynman diagrams (left) and the  $t\bar{t}$  signal diagrams only (right) for two different  $CP$ -even choices of the tensor form factors of (5). The vector form factors are fixed at their SM values of Eq. (6). The asymmetry for all the form factors fixed by Eq. (6) is shown in grey in each panel.

**Table 1**

Asymmetry (14) in % integrated in different  $t\bar{t}$  invariant mass ranges. The vector form factors are fixed at their SM values of Eq. (6). The complete set of the lowest order Feynman diagrams is included.

Form factors	$m_{t\bar{t}} < 450 \text{ GeV}/c^2$	$m_{t\bar{t}} \geq 450 \text{ GeV}/c^2$	Total
$f_2^R = f_2^L = \bar{f}_2^R = \bar{f}_2^L = 0$	$0.09 \pm 1.11$	$-0.27 \pm 0.45$	$-0.13 \pm 0.52$
$f_2^R = \bar{f}_2^L = 0.5, f_2^L = \bar{f}_2^R = 0$	$0.07 \pm 1.23$	$0.17 \pm 0.50$	$0.13 \pm 0.54$
$f_2^L = \bar{f}_2^R = 0.5, f_2^R = \bar{f}_2^L = 0$	$0.39 \pm 1.45$	$-0.42 \pm 0.58$	$-0.09 \pm 0.68$



**Fig. 3.** The charge-signed muon rapidity distribution for different  $CP$ -even (upper row) and  $CP$ -odd (lower row) combinations of the tensor form factors of (5). The vector form factors are fixed at their SM values of Eq. (6). The SM result is shown in grey in each panel.



The charge-signed lepton rapidity distributions  $(1/\sigma)d\sigma/d(q_l y_l)$ , where  $y_l$  is the rapidity of the charged lepton and  $q_l$  is a sign of its electric charge, are plotted in Fig. 3 for different  $CP$ -even (upper row) and  $CP$ -odd (lower row) combinations of the tensor form factors of (5). The vector form factors are fixed at their SM values of Eq. (6). The complete set of the lowest order Feynman diagrams is included in the calculation. The SM result is shown in grey and the results obtained with non-zero tensor form factors are depicted with boxes bounded by dashed lines in each panel. In spite of the fact that the anomalous  $Wtb$  coupling changes the total cross section of the top quark pair production by substantially altering the top quark width, the change in the charge-signed lepton rapidity distributions is hardly visible in the plots.

#### 4. Summary

The  $t\bar{t}$  invariant mass dependent FBA of top quark production and the charge-signed rapidity distribution of the lepton originating from the  $W$  boson from top quark decay at the Tevatron have been calculated to lowest order taking into account the anomalous  $Wtb$  coupling of the most general form, with operators up to dimension five [9]. It has been illustrated that even large values of the tensor form factors, exceeding the current limits [2], have rather little influence on the FBA. Also the charge-signed rapidity distribution of the lepton is very little affected by different  $CP$ -even and  $CP$ -odd combinations of the tensor form factors within the current limits.

#### Acknowledgements

This work was supported in part by the Research Executive Agency (REA) of the European Union under the Grant Agreement number PITN-GA-2010-264564 (LHCPHenoNet).

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